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THE EFFECT OF THE PARAMETERS OF THE MOLDING UNIT IN GLASS-MOLDING MACHINES ON THE NONSTATIONARY TEMPERATURE FIELD OF GLASS MOLDS

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The temperature field of glass molds in the case of their external cooling is considered. The temperature field is represented as a sum of two components: the stationary component not depending on time, and the component cyclically varying with time. The cyclic component is investigated for the case where the heat flows at the mold boundaries are harmonic functions of time. Ratios establishing the relationship between the mold temperature variations per cycle and the molding unit parameters, as well as the relationships between the optimum values of these parameters, are obtained. The amplitude of temperature variations on the mold working surface is calculated for different parameters of the molding unit.

Thermocyclic loads in various fields of engineering constitute a basic factor which determines or has a perceptible effect on equipment wear. Glass and casting molds, cylinders in internal combustion engines, and cutting tools can serve as examples [1]. Therefore, the solution of the problem of increasing the service life of this equipment is directly related to the problem of determination of the nonstationary temperature fields arising inside this equipment in the course of operation.

The solution of this problem is especially important for the glass industry, since fluctuations in temperature on the working surface of the mold not only determine the longevity of the mold, but the quality of molded articles as well and the very possibility of glass molding. The less the temperature fluctuations, the higher the quality of the glass product, since in this case the molding proceeds under more homogeneous conditions. Moreover, a decrease in the amplitude of temperature fluctuations makes it possible to raise the average temperature on the molding surface (without the danger of reaching the temperature of glass adhesion), which also improves the quality of glass articles [4, 5]. The amplitude of the mold temperature fluctuations is a factor limiting the efficiency of glass-molding machines, since with an increase in the thermal load on a mold, the temperature fluctuations on its working surface inevitably increase, and if their value exceeds the difference between the glass adhesion point and the temperature producing notches, "hammering," and other defects, the process of glass molding becomes impossible.

In order to determine the nonstationary temperature field of the glass mold, we decompose temperature $t(r, \tau)$ into two components: the stationary one $u(r)$ which does not depend on time, and the periodically varying with time $v(r, \tau)$:

$$t(r, \tau) = u(r) + v(r, \tau), \tag{1}$$

where r are space coordinates and τ is time, and consider each of them [6]. This approach is based on the following simple transformation: let $Q(\tau)$ be the heat flow density, and Q^* the average heat flow density on the mold working surface per cycle (assuming that the heat flow on this surface is homogeneous, i.e., does not depend on its coordinates). Obviously,

$$Q^* = \frac{1}{T}\int_0^T Q(\tau)d\tau,$$

where T is the molding cycle duration, i.e., the time interval between the penetration of two consecutive glass melt drops (for a parison mold) or two consecutive bullets (for a finishing mold) into the mold.

Let us denote the difference $Q(\tau) - Q^*$ by the function $q(\tau)$; then we see that the heat flow on the working surface of the mold is decomposed into two components: the stationary Q^* and the periodically changing with time $q(\tau)$, when

$$Q(\tau) = Q^* + q(\tau). \tag{2}$$

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The described transformations are illustrated in Fig. 1 for the step function $Q(\tau)$:

$$Q(\tau)=\begin{cases}Q_1, \text{at } nT\le\tau\le nT+BT\\ 0, \text{at } BT+nT\le\tau\le(n+1)T;\ n=0,1,2,\ldots,\end{cases}$$

where n is the number of the period; Q_1 is the heat flow density; B is part of the cycle during which the glass mixture stays in the mold.

Similarly, for the outer surface of the mold: represent the thermal efficiency coefficient $\alpha(\tau)$ as the sum

$$\alpha(\tau)=\alpha^* + \alpha_0(\tau)\,, \tag{3}$$

where α^* is the average coefficient of thermal efficiency on the mold outer surface per cycle, when $\alpha^* = 1/T\int_0^T \alpha(\tau)d\tau$, and $\alpha_0(\tau)$ is equal to the difference $\alpha(\tau)-\alpha^*$.

Substituting Eq. (1) into the heat conduction equation, and Eqs. (2) and (3) into the respective boundary conditions, we obtain two systems of equations, one of which, for $u(r)$, does not contain the variable τ at all. The stationary component of the mold temperature $n(r)$ is well studied [6]; therefore we will specify only the equations for determining the variable component $v(r,\tau)$. This is the heat conduction equation

$$\frac{\partial v}{\partial\tau}=a\Delta v\,, \tag{4}$$

where a is the temperature conductance of the mold material; Δ is the Laplace operator, and the boundary conditions

$$-\lambda\frac{\partial v}{\partial r}\Big|_{r=r_0}=q\ (\tau), \tag{5}$$

$$-\lambda\frac{\partial v}{\partial r}\Big|_{r=r_1}=\alpha_0(\tau+\tau_0)(u(r_1)-t_a)\times\left(1+\frac{v}{u(r_1)-t_a}\right)+\alpha^* v, \tag{6}$$

where λ is the heat conductance of the mold; t_a is the average temperature of the cooling agent (air) surrounding the outer surface of the mold [6].

The time interval τ_0 takes into account the possibility of the periodic processes of mold heating and cooling being asynchronous. For example, at $\tau_0>0$, the cooling of the mold begins τ_0 seconds prior to the moment in which glass melt (for the parison mold) or the bullet (for the finishing mold) gets into the mold. Thus, the variable heat flows at the mold boundaries excite the heat waves which propagate toward each other inside the mold wall. If the wall is thick, the waves do nor affect each other due to the high degree of absorption. If the mold wall is sufficiently thin, the amplitude of the resulting wave, owing to the interference, can become either higher or lower than the initial wave amplitudes.

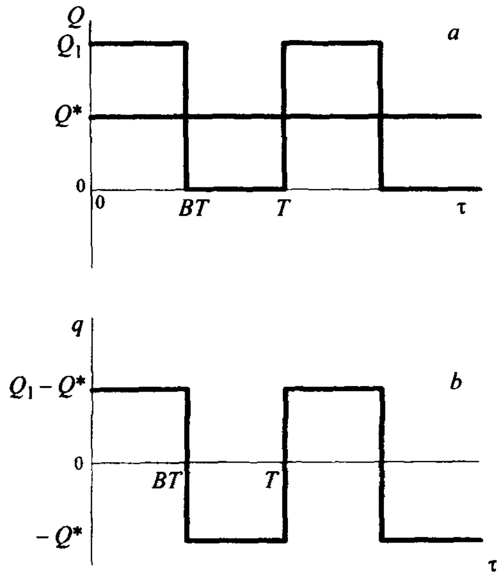

Fig. 1. Heat flow density on the mold working surface Q decomposed into the stationary Q^* and the cyclic q components: a) density of heat flow $Q(\tau)$ and the average heat flow density per cycle Q^* (stationary component); b) cyclic component of heat flow density.

The above model does not take into account heat transfer at the ends of the mold, and, consequently, the higher the amount of thermal energy abstracted from the molded glass article which is diffused on the mold outer surface, the more precisely will the heat transfer process in the mold be described. As was shown both in the experiments [6] and in industrial tests [7, 8], only a relatively small (~ 20%) part of the energy is abstracted through thermal radiation and heat transfer in the sites of the mold fastening. Therefore, the heat flow inside the mold wall can perceptibly differ from the radial heat flow only within a limited area near the upper and bottom ends of the mold.

Consider the simplest case where the variable components of the heat flows at the mold boundaries are described by harmonic functions depending on time. Let, for example,

$$q(\tau)=q_1\sin\omega\tau\,;$$

$$\alpha_0(\tau+\tau_0)=\alpha_1\sin(\omega\tau+\varepsilon)\,,$$

where $\omega=2\pi/T$ is frequency; $\varepsilon=\omega\tau_0$ is the phase difference between the processes of mold cooling and heating.

This case, which is the simplest for heat flows varying periodically with time, is at the same time a fundamental one, since any periodic functions $q(\tau)$ and $\alpha_0(\tau+\tau_0)$ can be decomposed into the Fourier series by sinus and cosines

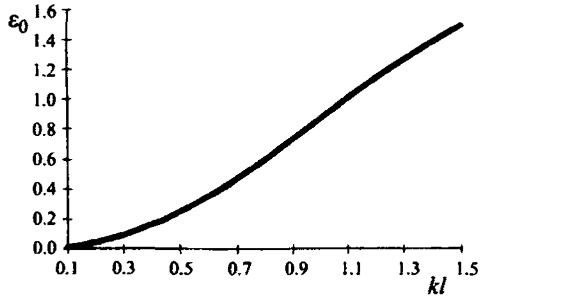

Fig. 2. Dependence of the optimum cooling phase ε_0 on the mold wall thickness l.

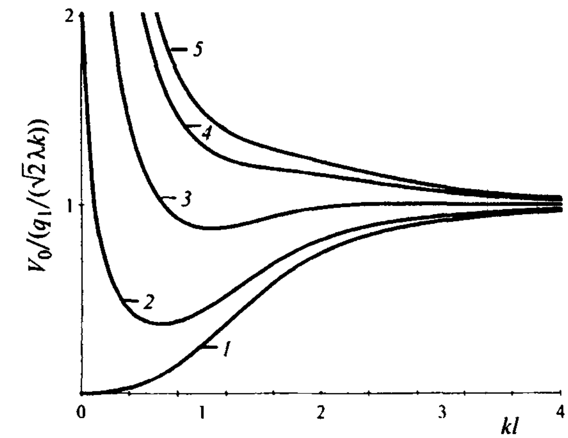

Fig. 3. Variable component of temperature on the mold working surface: *1* — $A = 1$, $\varepsilon = \varepsilon_0$; *2* — $A = 0.71$, $\varepsilon = \varepsilon_0$; *3* — $A = 0$; *4* — $A = 0.71$, $\varepsilon = \varepsilon_0 + \pi$; *5* — $A = 1$, $\varepsilon = \varepsilon_0 + \pi$.

(provided they are integrable and at least piecewise continuous, which is always fulfilled for the actual heat flows).

Equation (6) can be simplified by ignoring the term $v/(u - t_a) \ll 1$. The measurements performed on an IS-6 – 2 machine producing half-liter bottles of dark green glass [9] showed that the ratio between the temperature variations amplitude V and the mean temperature u on the outer surface of the mold is ~ 6%.

By approximating the cylindrical wall of the glass mold by a plane parallel wall, the solutions of Eqs. (4) – (6) can be expressed by elementary functions. Assuming that $x_0 = 0$, and $x_1 = l$ (l is the thickness of the mold wall), we find the variable temperature component for a depth of x, $v(x, \tau)$:

$$v(x, \tau) = V(x)\sin[\omega\tau + \arg(\bar{V}(x))], \qquad (7)$$

where $\arg(\bar{V}(x))$ and V are the argument and modulus, respectively, of the complex amplitude $\bar{V}$ equal to:

$$\bar{V}(x) = \frac{q_1}{(1+i)\lambda k} \times \frac{\mathrm{ch}[(1+i)k(l-x)] + \mathrm{Bi}^*\,\mathrm{sh}[(1+i)k(l-x)] - A\exp(i\varepsilon)}{\mathrm{sh}[(1+i)kl] + \mathrm{Bi}^*\,\mathrm{ch}[(1+i)kl]}, \qquad (8)$$

where i is the imaginary unit, $i^2 = -1$; $= \sqrt{\omega/2a}$ is the wave number; $\mathrm{Bi}^* = \dfrac{\alpha^*}{(1+i)\lambda k}$ is the modified Bio number; $A = \dfrac{\alpha_1[u(l) - t_a]}{q_1}$.

In our case, $A = 1$, since the heat flows on the mold surfaces are equal.

The real values of $|\mathrm{Bi}^*|$ in glass molding are not high. Thus, for the 2VV-12-01 machine equipped with a cooling system ensuring the most intense heat removal from the mold compared to other domestic glass-molding machines, $\alpha^* \approx 500$ W/(m$^2 \cdot$ K) [6], and assuming $T = 10$ sec, we get $|\mathrm{Bi}| \approx 0.05$. For other domestic machines $|\mathrm{Bi}^*|$ will be even lower, and for foreign machines with a closed cooling system, this value will be similar (we are not discussing here molds cooled by the verti-flow system). Therefore, in the computation of Eq. (7), the terms containing Bi* can be ignored.

The amplitude of temperature variations on the mold working surface V_0 is of practical interest, since its significant increase can bring about the production of defective articles and acceleration of the mold wear due to increased thermocyclic loads. As seen from Eq. (8), the value of the amplitude V depends on the mold wall thickness l and the cooling phase ε. Denote by ε_0 the cooling phase in which V_0 reaches the minimum level for a given value of l. By ignoring the members containing Bi*, we obtain from Eq. (8)

$$\varepsilon_0 = \arctan(\tan kl\ \mathrm{th}\, kl). \qquad (9)$$

The plot of the function $\varepsilon_0(l)$ is shown in Fig. 2. Figure 3 shows the dependence of the amplitude of temperature variations on the working surface on the mold wall thickness for $\varepsilon = \varepsilon_0$. As can be seen, with a sufficiently thick wall, the amplitude V_0 starting with a certain value of l_1 (when $kl_1 \approx 5.5$) does not depend at all on the mold wall thickness. Indeed, the temperature waves excited on the mold surfaces do not affect each other, the mold wall can be regarded as semi-infinite, and we arrive at the known [10] relationship

$$v = q_1/(\sqrt{2}k\lambda)e^{-kx}\sin\left(\frac{\omega\tau - \pi}{4} - kx\right).$$

At $l < l_1$, the interference of the temperature waves causes a monotonic decrease in the temperature variation amplitude on the molding surface, as the wall thickness increases (provided $\varepsilon = \varepsilon_0$), up to $V_0 = 0$ at $l = 0$ ($A = 1$). If the cooling phase ε differs from ε_0, the amplitude V_0 with a decrease in l will decrease more slowly than at $\varepsilon = \varepsilon_0$, and its minimum will be nonzero and will be attained at a certain

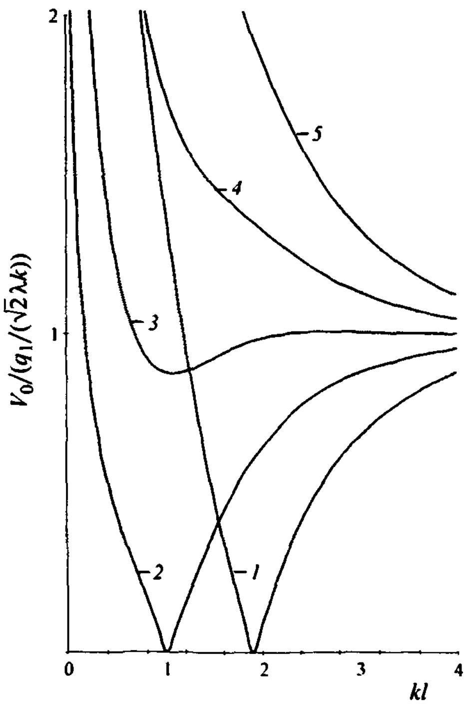

Fig. 4. Variable component of the mold working surface temperature: *1* — $A = 3.65$, $\varepsilon = \varepsilon_0$; *2* — $A = 1.41$, $\varepsilon = \varepsilon_0$; *3* — $A = 0$; *4* — $A = 1.41$, $\varepsilon = \varepsilon_0 + \pi$; *5* — $A = 3.65$, $\varepsilon = \varepsilon_0 + \pi$.

value $l = l_0 \neq 0$. A further decrease in $l < l_0$ causes a rapid increase in V_0 at $l \to 0$.

If ε significantly differs from ε_0, V_0 can monotonically grow with the decrease of l. In this case (for example, when cooling is delayed), before the "cooling wave" excited at the outer surface of the mold reaches the molding surface, the latter will be heated to a significantly high temperature (as $l \to 0$), close to the temperature of molded glass. This heating will be more intense the thinner the mold wall (and accordingly, the lower the mass and the heat capacity of the mold). The "cooling wave" which arrives virtually without absorption due to the low value of the wall thickness will stabilize the process, and yet, due to the delay, the cooling will last longer than required, which will cause a significant decrease in the temperature of the working surface (as $l \to 0$) to a level close to the initial temperature of the cooling agent. Obviously, the thinner the mold wall, the more intense is the cooling process (Fig. 3).

In the above described model of the heat transfer taking place in the mold in the course of glass molding, the parameter A was equal to 1. However, in the more general case, the heat processes at the mold boundaries can be described not by harmonic but by more complex periodic functions of time. Then, as these functions are decomposed into a Fourier's series, the amplitudes of the harmonics of one order at the opposite surfaces of the mold will not be equal and, accordingly, the parameter A can take an arbitrary value. In this case, the shape of the curve describing the dependence of the

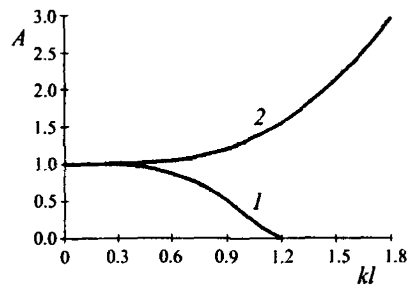

Fig. 5. Dependence between the parameter A and the wall thickness l at which the temperature wave amplitude minimum on the mold working surface is attained: *1*) $A(l_0)$ at $A < 1$; 2) $A(l_0)$ at $A > 1$.

amplitude of the working surface temperature variation V_0 on the mold wall thickness will be changed.

With $A < 1$ (A being a positive value), same as with $A = 1$, the amplitude of the variable component of the mold temperature, starting with a certain value of l_1 depending on A, decreases, as l decreases, at $\varepsilon = \varepsilon_0$. However, the curves have a minimum distinct from zero at $l_0 \neq 0$, and the value of this minimum and the value of l_0 are both functions of the parameter A. Figure 3 shows the dependences $V_0(l)$ for $A = 0.71$ (curves *2* and *4*) and $A = 0$ (curve *3*). The latter means that the mold is constantly chilled, i.e., $\alpha(\tau) = \text{const}$. Note that the specific shape of the curves $V(l)$ is determined by the parameter A: the greater is A, the wider and deeper the curve minimum, and the higher the value of l_1 starting with which the amplitude of temperature variations on the mold surface decreases to a minimum at $\varepsilon = \varepsilon_0$. And vice versa, at $\varepsilon = \varepsilon_0 + \pi$, the greater A, the sooner the temperature variations increase as the mold wall thickness increases. For all other values of ε the curves $V(l)$ lie within a region which is limited on one side by the "minimum" curve corresponding to $\varepsilon = \varepsilon_0$ and on the other side by the "maximum" curve corresponding to $\varepsilon = \varepsilon_0 + \pi$, for example, between curves *1* and *5* in Fig. 3 at $A = 1$, and between curves *2* and *4* for $A = 0.71$

If $A > 1$, the "minimum" curves $V_0(l)$ will always have a minimum equal to zero at a certain value of l_0 depending on A, i.e., $V_0(l_0) = 0$. At the same time, while for $A_1 \leq 1$ the value of l_0 decreases with an increase in A up to $l_0 = 0$ at $A = 1$, for $A > 1$, on the contrary, l_0 increases with an increase in A, and curve $V_0(l)$ has the specific shape at the minimum point (Fig. 4).

The plot establishing a relationship between the parameters A and l_0 is shown in Fig. 5. For a sufficiently large A (in fact, for $A > 3$) the value of l_0 can be approximately found as $l_0 \approx 1/(k \ln 2A)$.

For the purpose of our calculation, the glass mold wall was regarded as plane-parallel. Let us define the area of application of this approximation. It is well known that a cylindrical wall in thermal calculations can be approximated by a plane-parallel plate if the cylindric surface radius is significantly larger than the wall thickness, i.e., $r_0 \gg 1$. Since the re-

gion of effective decrease in the temperature variation amplitude corresponds to values of the mold thickness below 1 cm (Fig. 3 and Eq. (8)), the above cited relationships are true at least for the finishing molds used for bottle production, and even more so for the molds used to produce glass jars.

It seems reasonable to offer another criterion for the assessment of suitability of the above model for description of temperature variations inside a cylindrical wall. Taking into account that a decrease or increase in the temperature variation amplitude depending on the value of ε is determined by the effect of the temperature wave interference, the better the cylindrical temperature waves propagating in an actual mold can be approximated by the plane waves, the more precisely the results obtained for a flat wall will describe the processes taking place in the mold. Such approximation will be justified if the width of the wave-front significantly exceeds its length, i.e., $\Lambda \ll 2\pi r_0$ (Λ is the length of the temperature wave, $2\pi r_0$ is the width of the temperature wave-front). For a cast iron mold at $T = 10$ sec, $\Lambda \approx 1.2$ cm. Therefore, the criterion of applicability of the plane-parallel approximation will be $r_0/\sqrt{T} \gg 0.5 \times 10^{-3}$ for r_0 expressed in meters and T expressed in seconds.

The proposed approach to the description of glass mold temperature makes it possible to determine uniquely such significant molding parameters as the beginning of the mold cooling process (for periodic mold cooling) and the thickness of the mold wall. The obtained relationships can be accepted as a first approximation to precise results, since the heat flows at the mold boundaries were assumed to be harmonic functions of time. In order to use them in engineering designs, the effect of the type of time dependence of the specified heat flows on the temperature field should be investigated. However, being periodic functions of time, the heat flows at the mold boundaries can be decomposed into a Fourier series, i.e., represented as sums of harmonic functions. Thus, the obtained results can be used as instruments in such investigation.

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